NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

Technical Report
TR-6015-OCN

FOAM-FILLED FENDER DESIGN TO PREVENT HULL DAMAGE

by

R. David Curfman, P.E.
Special Assistant for Waterfront and Harbors
NAVFAC Criteria Office
Naval Facilities Engineering Command

December 1997

19990429 079

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to: Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 1997	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE

Foam-Filled Fender Design to Prevent Hull Damage

5. FUNDING NUMBERS

6. AUTHOR(S)

R. David Curfman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Facilities Engineering Command Code 15C
1510 Gilbert St
Norfolk VA 23511-2699

8. PERFORMING ORGANIZATION REPORT NUMBER

TR-6015-OCN

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Facilities Engineering Command Code 15C
1510 Gilbert St
Norfolk VA 23511-2699

10. SPONSORING/MONITORING AGENCY

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

To design a foam-filled fender system requires that the designer address four design criteria:

1) the applied berthing energy of the vessel,
2) the design climatological loads on the vessel, usually from wind and current,
3) the minimum stand-off distance between ship and pier, and
4) the allowable pressure on the vessel hull.

This paper proposes rational design criteria to prevent yielding of vessel hull plating while approaching or at the berth.

14. SUBJECT TERMS

Mooring, Fenders, Ships

15. NUMBER OF PAGES

12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT U	18. SECURITY CLASSIFICATION OF THIS PAGE U	19. SECURITY CLASSIFICATION OF ABSTRACT U	20. LIMITATION OF ABSTRACT U

EXECUTIVE SUMMARY

To design a foam-filled fender system requires that the designer address four design criteria:

    1) the applied berthing energy of the vessel,
    2) the design climatological loads on the vessel, usually from wind and current,
    3) the minimum stand-off distance between ship and pier, and
    4) the allowable pressure on the vessel hull.

This paper proposes rational design criteria to prevent yielding of vessel hull plating while approaching or at the berth.

Presently, facility designers use the method outlined in MIL-HDBK 1025/1 to calculate applied berthing energy. DM 26.4 defines the design wind criteria. The paper by Seelig, Kriebel, and Headland defines the design current criteria. Facility designers normally use a design wind velocity of 64 knot winds, unless a lower value is justified. Design current velocity is normally the average current velocity at the locale.

The objective of fender design is to prevent damage to the vessel and pier. Since the source of wind and current loads are from expected events and the duration of berthing and breasting loads are of medium duration, the following design criteria is recommended for allowable bending stress in the ship hull:

    For Berthing, $F_b = 0.67 F_y$
    For Breasting, $F_b = 0.80 F_y$

Considering this approach, Enclosures 1 and 2 contain maximum hull pressures causing hull yielding for surface ships.

FOAM-FILLED FENDER DESIGN
TO PREVENT HULL DAMAGE

1. Introduction

To design a foam-filled fender system requires that the designer address four design criteria --
    1) the applied berthing energy of the vessel,
    2) the design climatological loads on the vessel, usually from wind and current,
    3) the minimum stand-off distance between ship and pier, and
    4) the allowable pressure on the vessel hull.
The literature addresses the first three considerations extensively. However, research regarding design criteria for allowable hull pressures is scarce. Perhaps this is due to the lack of interface between facility designers and naval architects. This paper proposes rational foam-filled fender design criteria to prevent yielding of the hull plating when the vessel breasts or berths at the pier. First, we will review the current practice for the determination of berthing energy and climatological loads.

2. Applied Berthing Energy

Within the Naval Facilities Engineering Command, engineers normally calculate applied berthing energy by the method outlined in MIL-HDBK 1025/1[i], which relies on approach velocities and ship displacement,. Research from the mid 1960's by the Naval Civil Engineering Laboratory (NCEL), now the Naval Facilities Engineering Service Center (NFESC), is the basis for the method. Recently, NFESC reexamined the method and concluded that improvement in the theory is necessary[ii]. The Office of Naval Research (ONR) is supporting further research in this area to quantify the effects of shallow water and dynamic response. Until this work is completed in 1998, engineers will continue to use the MIL-HDBK 1025/1 method. The forces imparted during berthing against a foam-filled fender are generally of medium duration, generally between 2 and 20 seconds. Therefore, designers should not include a load increase for "impact" as noted in Paragraph 5.4.4.3 of MIL-HDBK 1025/1.[iii]

3. Wind Loading

In the 1980's, NCEL performed extensive model tests on a variety of ships and developed procedures to calculate wind loads on vessels[iv]. These methods appear in DM 26.4[v] and DM 26.5[vi] for design of mooring and fendering. A cursory comparison of these results with recent work sponsored by the Naval Sea Systems Command (NAVSEA) confirms that the NCEL results are very close to actual wind tunnel tests performed.[vii] Regarding design wind velocity, NAVSEA uses 50 knots,[viii] whereas NAVFAC normally uses 64 knots - the minimum wind velocity to classify a storm as a hurricane and the speed at which most ships would leave the berth and put out to sea. The forces applied during breasting may be of a duration as long as 6 hours from combined current loading or wind loading. Movement from the berth is not always practical due to ship maintenance or damaged conditions. Therefore, engineers should design berths expected to be occupied during a hurricane for the elevated wind level.

4. Current Loading

The determination of loads on ships from current forces has been developing over the years.[ix,x] NFESC evaluated various methods and concluded that engineers should use the work by Seelig, Kriebel, and Headland to determine current forces.[xi] Future revisions to DM 26.4 and DM 26.5 NAVFAC will include this technology. Regarding design current velocity, NAVSEA recommends 3 knots,[xii] whereas NAVFAC recommends using the average current velocity.[xiii]

5. Ship configuration

A variety of materials, including steel, aluminum, wood and composites form the hulls of naval vessels. Most ships, however, are constructed of carbon steel. This report examines only carbon steel hulls fabricated from grades of steel varying from 34 ksi yield to 100 ksi yield. To design these hulls, Naval Architects use the "Structural Design Manual for Naval Surface Ships."[xiv]

The composition of a typical Navy hull is steel plating welded to longitudinal (horizontal) stiffeners at two to four feet on center. The stiffeners span from five to twenty feet depending on the vessel. Generally, the stiffeners are of sufficient strength to preclude failure from fender loading. However, the hull plating may yield when subjected to a uniformly distributed overload on the panel.

Generally, if there is an accidental situation, it is the fender system that should be "sacrificed." Loss of the berth or damage to the ship has a much more serious consequence than damage to the fender system, since it is much more expensive to repair a ship's hull than rehabilitate a damaged fender system.[xv]

6. Foam filled fender characteristics

Cross-linked foam composes the core of most foam-filled fenders. The foam deforms elastically when subjected to an applied force. The relationship between pressure and deflection is non-linear, due in part to the shape of the fender. See Attachment A.[xvi] To prevent damage to the fender, manufacturers normally recommend that the fender not exceed 60% compression under design conditions. At this deflection, most fenders exhibit a reactive pressure of approximately 25 psi.

7. Design Criteria

No model code addresses design of steel ship hulls subjected to berthing and breasting loads. However, several codes generally address steel member design. A review of these codes below annotates the respective applicability to allowable hull pressures. The basic equation defining plate capacity is $M_B < \alpha F_y S_x$, where α = yield stress reduction coefficient -- the coefficient to be determined for each material, M_B = the allowable bending moment, F_Y = the yield stress in the hull plating, and S_X = the section modulus. For design criteria, the hull should sustain no damage during berthing or breasting.

7.1   AISC, "Manual of Steel Construction, Allowable Stress Design"

The American Institute of Steel Construction (AISC) published the Manual in 1989, but superseded it by the Load and Resistance Factor Design method.[xvii] However, it provides an excellent starting point for discussion. The code addresses impact concerning cranes, but not ship impact. Section A5.2. allows an increase in the allowable stress of 1/3 for members subjected to wind loading acting alone or in combination with live loads. Section F2.1. gives the maximum allowable stress in a plate bent about its weaker access as $F_b = 0.75\ F_y$. Therefore,

> For Berthing, $F_b = 0.75\ F_y$
> For Breasting, $F_b = (1.333)0.75\ F_y = 1.00\ F_y$

7.2   NAVSEA, "Structural Design Manual for Naval Surface Ships"

This code does not address fender loads on ships, however it does provide allowable stresses for steel hull plating.[xviii] Most ship designers attempt to design to a "Safe Life Policy," which means that the strength of the component should rule out any damage or failure throughout the life of the ship. The Manual recommends a safety factor of 1.25 (yield strength to allowable working strength) but does not specifically address the allowable stress in plates subjected to lateral loads. However, conversations with NAVSEA indicate that a value of $F_b = 0.80\ F_y$ is appropriate. The guidance provides no reduction for load combinations. Therefore,

> For Berthing, $F_b = 0.80\ F_y$
> For Breasting, $F_b = 0.80\ F_y$

7.3   ASCE 7-95, "Minimum Design Loads for Buildings and Other Structures"

For Allowable Stress Design, the Standard recommends a load combination factor of 1.0.[xix] The code also recommends that one use a reduction factor for combined variable loads acting together. However, the Code does state that this condition "shall not be less than the effects from the load combination of the dead load plus the load producing the largest effects." Therefore, using the AISC Manual concomitant with the ASCE Standard,

> For Berthing, $F_b = 1.0\ (.75)\ F_y = .75\ F_y$
> For Breasting, $F_b = 1.0\ (.75)\ F_y = .75\ F_y$

7.4   MIL-HDBK 1025/1, "Piers and Wharves"

This criteria developed by NAVFACENGCOM puts forth several recommendations concerning fender and pier design.[xx] Using an allowable stress in the steel of $F_b = 0.75\ F_y$, Table 6 recommends:

For Berthing, $F_b = 1.0(1.0)(.75) F_y = .75 F_y$
For Accidental Berthing, $F_b = .67(1.0) F_y = .67 F_y$
For Breasting, $F_b = 1.0(1.4)(.75) F_y = 1.05 F_y$
   or
For Breasting $F_b = [1.0(\text{Current Load}) + 0.3(\text{Wind Load})]*1.25 (.75) F_y$
   $F_y = [0.94(\text{Current Load}) + 0.28(\text{Wind Load})]* F_y$

Table 6 provides guidance specifically for pier design and not fenders. However, the load combination factors do provide valuable insight into potential failure modes. The handbook also recommends that engineers design fenders as Class B structures according to AASHTO.[xxi] This method renders the latter solution as

For Breasting, $F_b = 1.0(1.25)(.75) F_y = 0.94 F_y$

Paragraph 5.4.4.3 provides guidance relating to steel fendering systems as follows:

For Berthing, $F_b = 0.80 F_y$

8.   Plate Analysis

Enclosures 1 and 2, from NAVSEA, annotates the hull pressure and reaction causing plate yielding (F_y) for a variety of conditions:
   1) Foam-filled fender load over the entire panel
   2) A short camel spanning between panels
   3) A 1 ft. x 1 ft. load applied at the center of a panel, such as a buckling fender
   4) A vertical line load carried by a stiffener similar to a battered fender pile
   5) A foam-filled fender load carried by a stiffener
   6) A 4 ft. long foam-filled fender load carried by a frame.

9.   Recommended Design Criteria

The objective of fender design is to prevent damage to the vessel and pier. MIL-HDBK 1025/1 recommends examining the fender system for failure by increasing the design berthing energy by 50%. Under this condition, the hull plating should not exceed the yield stress of the hull, F_Y. Since the design wind and current velocities occur relatively frequently and are not probabilistically based, and the durations of berthing and breasting loads are relatively medium, we recommend that the design criteria to prevent damage to the hull be modified as follows.

Under design conditions, the resulting bending stress in a vessel hull component caused by the fender system reaction force should not exceed 0.67 F_y during berthing and 0.80 F_y during breasting. For a variety of conditions, the pressure and forces causing plate yielding are noted in Enclosures 1 and 2. Therefore, use 0.67 x the values in Enclosure 1 for Berthing Analysis and 0.80 x the values in Enclosure 1 for Breasting Analysis.

Designers should not use an allowable overstress and need not check for the accidental condition. Both conditions are accounted for in the criteria.

6.0 Conclusion

In summary, the above documentation presents the following conclusions concerning allowable hull pressures:

    a. The design wind and current velocities occur relatively frequently and are not probabilistically based.
    b. The durations of berthing and breasting loads are relatively medium.
    c. Facility designers should strive to prevent damage to the vessel as much as practicable.

Considering the above information, we propose the following design criteria to protect the ship hull:

    For Berthing, $F_b = 0.67 \, F_y$
    For Breasting, $F_b = 0.80 \, F_y$

Enclosure (1) MAXIMUM ALLOWABLE HULL CONTACT PRESSURES AND LOADS

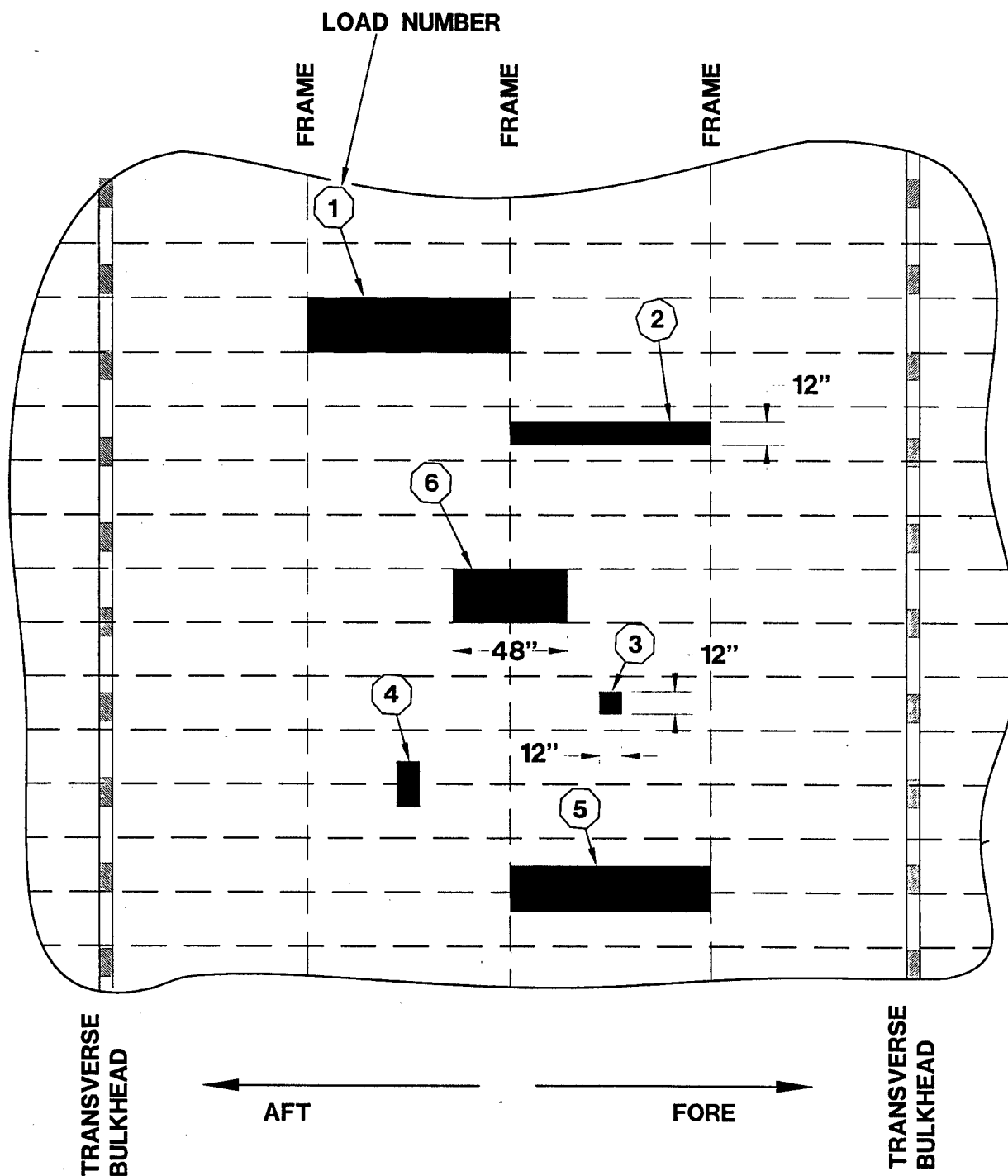| Loading Number	1		2		3		4		5		6	
Loading Type	Uniform load over entire panel		Partial unit load over Panel mid		Centered Load on panel		Load carried by one stiffener		Soft Fender in Line w Stiffner		Soft fender in Line w Frame	
Method of Calcln	Ref (1)		Ref (2)		Ref (2)		Ref (3)		Ref (3)		Ref (3)	
Max allowable Pressure/Load	q	P	q	P	q	P	q	P	q	P	q	P
Ship	psi	kips	psi	kips	psi	kips	psi	kips	psi	kips	psi	kips
LKA -113	20	68.0	26	45.7	53	7.7	229	16.5	9	33.5	----	----
LPD - 4	13	38.2	19	22.1	46	6.7	152	13.7	9	26.9	----	----
LHA - 1	21	41.5	27	27.2	54	7.7	555	40.0	39	78.5	----	----
LSD - 36	15	52.9	28	32.1	62	8.9	167	18.0	10	35.4	----	----
LST - 1179	11	25.8	15	17.3	30	4.3	305	21.9	19	43.2	----	----
AD - 37	20	79.3	23	45.7	53	7.7	196	14.1	7	27.9	172	198.3
AE - 26	13	42.1	22	28.6	46	6.7	245	22.0	13	43.4	171	245.8
AFS - 1	20	51.4	27	34.6	53	7.7	452	32.6	25	64.2	103	118.8
AOE - 1	20	45.9	27	30.8	53	7.7	675	48.6	42	95.6	----	----
AO - 177	20	51.7	27	35.4	53	7.7	435	31.3	24	61.7	----	----
TAO - 187	20	71.8	31	44.3	73	10.4	509	45.8	25	90.4	----	----
AOR - 1	44	127.5	55	79.7	120	17.2	811	58.4	40	115.3	----	----
ARS - 38	21	41.3	27	27.2	63	9.0	218	15.7	15	30.8	----	----
ARS - 50	20	45.9	27	30.8	53	7.7	155	11.2	10	22.0	----	----
AS -36	15	31.4	18	15.9	52	7.5	308	33.3	30	65.2	74	127.9
AR - 5	19	64.4	34	39.1	75	10.8	168	18.2	10	35.8	----	----
CGN - 36	22	43.7	29	28.8	49	7.0	380	27.3	27	53.7	134	154.4
CGN - 38	21	48.6	28	32.6	56	8.1	368	26.4	23	51.9	----	----
CV - 66	30	287.9	60	171.4	167	24.0	631	75.7	16	150.4	----	----
CVN - 68	22	211.5	44	125.9	122	17.6	920	110.4	23	219.3	----	----
BB - 61	12	68.1	26	35.6	83	12.0	730	105.1	38	207.4	----	----
CG - 26	18	52.2	26	30.1	64	9.2	268	24.1	17	47.5	----	----
CG - 47	11	27.3	14	16.3	30	4.3	408	33.1	25	65.1	126	163.5
DD - 963	11	27.3	14	16.3	30	4.3	286	23.1	18	45.5	114	148.1
DDG - 2	36	82.7	48	55.5	96	13.8	435	31.3	27	61.7	----	----
DDG - 37	41	130.1	70	80.1	171	24.6	590	58.4	36	115.0	----	----
DDG -993	10	27.1	14	16.3	30	4.4	408	33.1	25	65.1	117	151
FF - 1052	11	23.6	15	16.3	29	4.1	302	21.8	20	42.8	94	107.7
FFG - 7	15	29.6	17	19.2	29	4.1	294	17.7	18	34.8	----	----
CG - 16	18	52.2	26	30.1	64	9.2	268	24.1	17	47.5	----	----
AGOR - 16	9	23.8	19	5.6	25	3.5	251	18.1	31	18.1	----	----
AGOS - 19	16	27.8	21	18.4	42	6.0	486	35.0	40	68.5	----	----
TAGS - 45	87	54.4	89	51.3	118	16.9	1519	59.2	184	114.8	385	239.9
AOE - 6	13	50.3	18	28.9	46	6.7	540	48.6	18	69.5	----	----
DDG - 51	8	21.9	11	12.5	26	3.8	196	17.1	12	33.6	61	85.5
FFG - 50	15	29.6	19	21.9	33	4.8	361	21.6	22	42.6	----	----
LHD - 1	20	40.8	30	30.1	81	11.5	160	11.5	11	22.7	365	279.9
LSD - 41	14	44.1	24	27.2	50	7.2	482	49.1	30	96.7	----	----
LSD - 49	16	52.2	28	32.2	59	8.5	579	59.1	36	116.3	----	----
LX(LPD 17)	21	56.3	30	35.0	64	9.2	1328	111.5	80	219.7	----	----
MCM - 1	28	93.8	70	31.9	114	16.4	93	10.6	7	10.6	----	----
PC(PGG 1)	16	4.5	16	4.5	20	2.8	353	12.7	83	23.8	----	----
CVN - 72	15	176.3	43	122.4	123	17.7	753	108.4	19	215.4	----	----
YC - 1523	9	21.6	20	5.6	25	3.6	152	10.9	19	10.9	----	----
YP(108)	33	54.7	58	12.6	62	8.9	47	2.5	8	2.5	----	----
YFN - 1254	9	21.6	20	5.6	25	3.6	152	10.9	19	10.9	----	----
LPH - 2	14	94.7	23	52.7	62	8.9	383	41.3	12	82.0	----	----
YTT - 9	11	33.6	24	6.8	30	4.3	139	10.0	17	10.0	----	----
ARDM - 5	14	26.8	20	16.9	41	5.9	210	16.4	17	32.1	----	----

Ref: (1) q=fy(t)^2/(kb^2) from "Theory of Plate and Shells" by Thimoshenko.

(2) q=fy(t^2)/ka1b1) from "Formulas for stress and strain" by Rorark, and from plate reponse method by Dervine, DTRC.

(3) w=10fy(SM)/(2LA-A^2) from Simple Beam Theory, and Navsea Ship Structural Design Criteria.

Where Fy=Yield stress, k=6Beta

Enclosure (2) HULL LOADING NUMBERS
Typical Shell Expansion for Longitudinally-Stiffned Ships

LOAD NUMBER

FRAME

FRAME

FRAME

① ② 12"

⑥

←—48"—→ ③ 12"

④

12" → ←

⑤

TRANSVERSE BULKHEAD

TRANSVERSE BULKHEAD

←———— AFT   FORE ————→

Endnotes

[i] <u>Piers and Wharves</u>. (1987). Military Handbook 1025/1, Naval Facilities Engineering Command, Alexandria, VA. October 30, 1987.

[ii] Davis, D.A. and Huang, E.T. (1994). "Ship Berthing Forces - Initiation Decision Report," TM-2094-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA. September 1994

[iii] <u>Piers and Wharves</u>. (1987).

[iv] Owens, R. And Palo, P. (1982). "Wind-Induced Steady Loads on Ships," TN-1628, Naval Civil Engineering Laboratory, Port Hueneme, CA. April 1982.

[v] <u>Fixed Moorings</u>. (1986). Design Manual 26.4, Naval Facilities Engineering Command, Alexandria, VA. April 1986.

[vi] <u>Fleet Moorings</u>. (1985). Design Manual 26.5, Naval Facilities Engineering Command, Alexandria, VA. June 1985.

[vii] <u>Wind Induced Forces Acting on U.S. Navy Ships</u>. (1994). AME Technical Report 4373-137. Advanced Marine Enterprises, Inc., Arlington , VA. October 1994.

[viii] <u>Calculations for Mooring Systems</u>. (1987). DDS-582-1. Naval Sea Systems Command, Washington, DC. January 1987.

[ix] Palo, P. and Owens, R (1982). "An Assessment of State-of-the-Art Methods for Calculating Current Loads on Moored Ships," TN-1633, Naval Civil Engineering Laboratory, Port Hueneme, CA. June 1982.

[x] Karnoski, Stephen R. and Palo, Paul A. (1986). "FLEETMOR Validation Report," TM-44-86-02, Naval Civil Engineering Laboratory, Port Hueneme, CA. October 1986.

[xi] Seelig, W. and Palo, P. (1994). "Assessment of Present Navy Methods for Determining Mooring Loads at Single-Point Moorings," TR-2018-OCN, Naval Facilities Engineering Service Center, Port Hueneme, CA. May 1994

[xii] <u>Calculations for Mooring Systems</u>. (1987).

[xiii] <u>Fleet Moorings</u>. (1985).

[xiv] <u>Structural Design Manual For Naval Surface Ships</u>. (1976). NAVSEA 0900-LP-097-4010, Naval Ship Weapons Engineering Station, Port Hueneme, CA. December 1976.

[xv] <u>Piers and Wharves</u>. (1987).

[xvi] <u>Sea Cushion Design Manual</u>. (1982). Seaward International, Inc., Falls Church, VA

[xvii] <u>Manual of Steel Construction</u>. (1989). American Institute of Steel Construction, Inc., Chicago IL. July 1989.

[xviii] <u>Structural Design Manual For Naval Surface Ships</u>. (1976).

[xix] <u>ASCE Standard: Minimum Design Loads for Buildings and Other Structures</u>. (1995). ASCE 7-95. Draft copy, American Society of Civil Engineers, New York, NY. May 1995.

[xx] <u>Piers and Wharves</u>. (1987).

[xxi] <u>Standard Specifications for Highway Bridges</u>. (1989). American Association of State Highway and Transportation Officials (AASHTO), Washington, DC.